# A CORRELATION OF ROTARY DRUM COOLER-FLAKER HEAT TRANSFER

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## ABSTRACT

A theoretical mathematical expression is presented which effectively correlates rotary drum cooler-flaker design and operating variables. Its application eliminates design uncertainties introduced by the previous empirical approach, and allows adjustment of operating variables for optimum performance with a minimum of experimentation. The proposed equation is derived from the general statement for unidirectional unsteady state heat conduction in an infinite film layer. The simplifications made in the derivation include the assumption that the thermal properties of the liquid and solid phases do not differ greatly and that the latent heat of solidification averages in the sensible heat effect.

Extensive tests conducted with plant-size drum cooler-flakers show experimental results to be in excellent agreement with data predicted by the suggested expression. Process stream exit temperatures correspond to within a standard deviation of two percent (±3%) over wide ranges of primary operating variables. It is felt that the results of this work will prove to be of value in cooler-flaker sizing and the choice of optimum operating conditions.

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## INTRODUCTION

Rotary drum cooler-flakers are commonly used to continuously cool, solidify, and flake melts. In recent years they have widely displaced equivalent batch processing equipment since they conserve processing time and working space and eliminate the necessity of finished product crushing and grinding prior to storage and shipment. The operation and the construction of the flaking machines are so simple that they can be applied to the processing of practically all organic and inorganic chemical products that display a definite melting point and possess a truly crystalline solid structure at above ambient temperatures. The only limitation placed on a more extensive application of rotary drum cooler-flakers to materials meeting this melting point specification is the lack of a firm design basis and the difficulty in establishing optimum operating conditions. This has often limited new installations to the processing of previously tried systems.

Flaker sizing and design to date is largely based on a backlog of processing information available to the equipment manufacturers, and on extensive, time consuming pilot plant tests. A complete empirical-statistical evaluation of flaker performance is impractical due to the complex inter-relationship of the numerous operating and design variables and the inaccessibility of sufficient data taken on a common basis. This work was therefore initiated with the object of deriving a fundamental theoretical solution to the rotary flaker heat transfer performance which would serve as a springboard to a rational approach to flaker sizing and the choice of optimum operating conditions. This paper covers the method of mathematical analysis chosen and demonstrates the excellent agreement of the results of this analysis with available experimental data.

## FLAKER OPERATION

The operation of rotary drum cooler flakers is illustrated in the sketch of Figure 1. The flaker, or cooling drum, is mounted on hollow tunnions which are set in bearings. The drum dips to a depth, h, into a shallow pan filled with the molten process material at temperature $T_i$. A variable speed

drive powers the drum which picks up a film of L M lb/hr of processing material. The film is cooled and solidified during film-drum contact time, b, and then scraped (flaked) from the drum surface by a doctor blade. The flake discharge temperature is $T_o$. The drum surface may be cooled by cooling water, a brine solution, or a refrigerant, sprayed on the inner drum periphery through manifolded nozzles. At high coolant rates with low coolant temperature drops the coolant temperature may be set at t, the arithmetic average of inlet and outlet temperatures $t_i$ and $t_o$. The process film thickness is shown as R.

Primary and secondary operating variables are listed in Table I. The secondary variables are described as functions of the primary units. Of the primary operating variables the flake discharge temperature, $T_o$, is of greatest importance since product caking and sintering characteristics on transfer and storage are directly related to it. On the same basis this temperature usually limits the capacity of given size flaking units.

## TABLE I

## PRIMARY AND SECONDARY VARIABLES - FLAKER PROCESSING

Primary Variables:

| | | |
|---|---|---|
| $T_o$ | - | Process Stream, Discharge Temperature, °F |
| $T_i$ | - | Process Stream, Feed Temperature, °F |
| L | - | Processing Rate, M lb/hr |
| $t_i$ | - | Cooling Water, Feed Temperature, °F |
| $t_o$ | - | Cooling Water, Discharge Temperature, °F |
| rpm | - | Drum Rotary Speed |
| d | - | Drum Diameter, ft |
| l | - | Drum Width, ft |

Secondary Variables:

| | | |
|---|---|---|
| R | - | f (L)(rpm)(d)(l) - Process Film Thickness |
| G | - | f $(T_i)(T_o)(L)(t_i)(t_o)$ - Cooling Water Rate |
| h | - | f (rpm)$(L)(T_i)(T_o)$(l) - Depth of Drum Immersion |
| b | - | f (rpm) - Contact Time |

## MATHEMATICAL MODEL

The mathematical model chosen to describe the flaker operation is that of unidirectional unsteady state heat transfer in an infinite film layer. Figure 2 serves as an illustration. Since the temperature gradient in the X direction of heat transfer is usually $10^3$-$10^4$ times that in the Z direction, and since ideally no temperature gradient exists in the Y direction, unidirectional transfer of heat is postulated to be a valid approximation for this case. In this model the process film layer with thickness R is exposed for a time interval, b, to the drum surface at temperature t. The amount of heat, $Q_x$, removed from the process film is a function of the film-drum contact time. Boundary conditions may be defined as follows:

| | | | |
|---|---|---|---|
| At | $b = 0$ | , | $T = T_i$ |
| At | $b = \infty$ | , | $T = t$ |
| At | $x = 0$ | , | $T = t$ |

The partial differential equation descriptive of the heat transfer mechanism depicted in Figure 2 is given in its general form in Equation (1).

$$\delta T/\delta b = (k/c\rho)\,\delta^2 T/\delta X^2 \qquad (1)$$

The application of this equation to the flaking process involves the validity of the following assumptions:

1. Negligible heat loss, process film to atmosphere. (Experimentally shown not to exceed 15% of total heat transfer).

2. One hundred percent lateral drum coverage. (For maximum utilization flakers are operated at $>95\%$ coverage).

3. Greater than ten ratio of d/R. (This ratio is in the $10^4$ range in plant operation).

4. Incremental removal of latent heat of solidification in the X direction during the cooling process in the same proportion as heat transfer across the interphase. (The film temperature gradient insures this).

5. Approximately constant k within operational temperature limits.

6. Approximately constant ratio of $(k/c\rho)$ within operational temperature limits.

MATHEMATICAL SOLUTION

As indicated, assumptions 1-3 hold for most plant flaker applications. Limiting the application of Equation 1 to chemical

process materials exhibiting physical properties within the limitations of assumptions 4-6, Equation 1 may then be solved by application of a Fourier Series expansion as previously demonstrated by Sherwood and Reed to yield Equation 2.[1] Thus for $(k/c\rho)(b)/R^2 \geqq 0.5$ :

$$\ln E = \ln(8/\pi^2) - (\pi^2/4)(k/c\rho)(b/R^2) \tag{2}$$

The expression E here represents the ratio of the sensible heat remaining in the flaked product above datum temperature t over all the heat removed in cooling to datum temperature t, i.e., an inverse measure of the cooling efficiency. Inclusion of the latent heat term follows assumption 4 :

$$E = (T_o - t)\Big/(T_i - t + \Delta H_s/c) \tag{3}$$

The contact time b and film thickness R may, in Equation 2, be expressed in terms of primary operating variables as follows:

$$b = (0.0125)\text{rpm}^{-1} \tag{4}$$

$$R = (5.3)(L)\Big/(\rho)(\text{rpm})(d)(l) \tag{5}$$

Equation 4 predicates a drum circumferential film coverage of 270 degrees. The substitution of the primary

operating variables of Equation 4 and 5 into Equation 2 results in the general correlating equation defined by Equation 6.

$$\ln\left[\frac{T_O - t}{T_1 - t + \Delta H_s/c}\right] = -0.21 - 1.092 \times 10^{-3}\left(\frac{k\rho}{c}\right)\left(\frac{rpm}{L^2}\right)(dl)^2 \qquad (6)$$

This expression demonstrates that the inverse of the cooling efficiency of a rotary drum cooler flaker is a logarithmic function of the drum rotary speed, the square of the drum area, and the inverse square of the processing rate. Processing stream physical properties are represented in the term $\left(\frac{k\rho}{c}\right)$ as affecting the cooling operation.

## RESULTS

To test the validity of Equation 6, available flaker operational plant data were taken with a 48 in. x 28 in. (drum dimensions) flaker over a wide range of operating conditions. Upon insertion into Equation 6 the expected flake discharge temperature, $T_O$, was calculated. A comparison of these calculated values of $T_O$ to experimentally measured values showed a standard deviation of less than two percent. An example of the test information received with an arbitrary organic intermediate is shown in Table II.

TABLE II

APPLICATION OF EQUATION 6 TO ACTUAL OPERATING DATA

| $T_i$ °F | $T_o$ °F | t °F | L M lb/hr | rpm | $\frac{T_o - t}{T_i - t + \Delta H_s/c}$ | $T_o$ by Eqn.6 | ± % Error, $T_o$ Calculated from $T_o$ Experimental |
|---|---|---|---|---|---|---|---|
| 342 | 219 | 139 | 3.04 | 11 | 0.267 | 225 | +2.7 |
| 342 | 194 | 141 | 2.48 | 10 1/3 | 0.177 | 193 | -0.5 |
| 342 | 193 | 141 | 2.45 | 10 1/3 | 0.174 | 192 | -0.5 |
| 342 | 197 | 147 | 2.47 | 11 | 0.171 | 194 | -1.5 |
| 341 | 195 | 140 | 2.47 | 10 | 0.184 | 197 | +1.0 |
| 340 | 201 | 140 | 2.53 | 11 | 0.205 | 198 | -1.5 |
| 340 | 172 | 143 | 1.65 | 6 1/3 | 0.099 | 175 | +1.7 |
| 337 | 174 | 142 | 1.73 | 6 1/3 | 0.109 | 174 | ±0.0 |
| 342 | 166 | 146 | 1.56 | 6 | 0.068 | 167 | +0.6 |
| 342 | 164 | 146 | 1.52 | 6 | 0.062 | 167 | +1.8 |
| 345 | 155 | 146 | 1.13 | 4 1/2 | 0.030 | 154 | -0.7 |

Figure 3 plots the data of Table II. The correlating equation shown was derived from Equation 6, by insertion of the corresponding drum dimensions of d = 48 in. and l = 28 in. and the physical properties of the organic intermediate.

Preliminary data received from tests with an additional 48 in. x 60 in. flaker unit further substantiated the excellent agreement of plant operational data with that predicted by Equation 6.

## CONCLUSIONS

A mathematical expression was derived which effectively correlates rotary drum flaker design and operating variables for processing materials showing little change in thermal properties during cooling and solidification. The expression fits actual operating data within a standard deviation of two percent, based on flaker discharge temperature. Based on this excellent agreement, the expression should be useful as a basis for rotary drum cooler-flaker design and the choice of optimum operating conditions.

## NOMENCLATURE

| | | |
|---|---|---|
| $G$ | = | Coolant rate, lb/hr |
| $\triangle H_s$ | = | Latent heat of solidification, Btu/lb |
| $L$ | = | Processing rate, M lb/hr |
| $R$ | = | Process film thickness, ft |
| $T$ | = | Process film, average cross sectional temperature, °F |
| $T_i$ | = | Process material, feed temperature, °F |
| $T_o$ | = | Process material, discharge temperature, °F |
| $b$ | = | Process film, drum surface contact time, hr |
| $c$ | = | Process material heat capacity, Btu/lb/°F |
| $d$ | = | Drum diameter, ft |
| $h$ | = | Depth of drum immersion, ft |
| $k$ | = | Process material thermal conductivity, Btu-ft/ft$^2$/°F/hr |
| $l$ | = | Drum width, ft |
| $t$ | = | Average coolant temperature, °F |
| $t_i$ | = | Coolant inlet temperature, °F |
| $t_o$ | = | Coolant exit temperature, °F |
| $\rho$ | = | Process material density, lb/ft$^3$ |

## REFERENCE

(1) Sherwood, T. K. and Reed, C. E. : "Applied Mathematics in Chemical Engineering," 1st Ed., p. 220, McGraw-Hill Book Company, Inc., 1939.

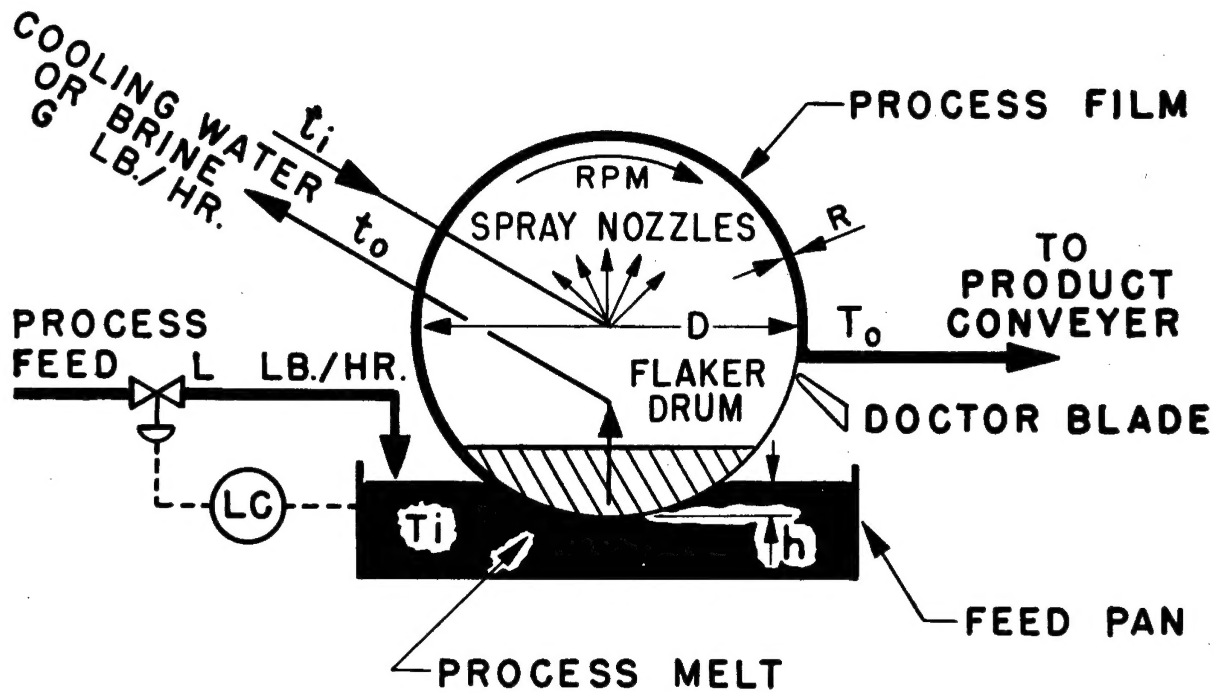


FIGURE 1

ROTARY DRUM COOLER-FLAKER OPERATION

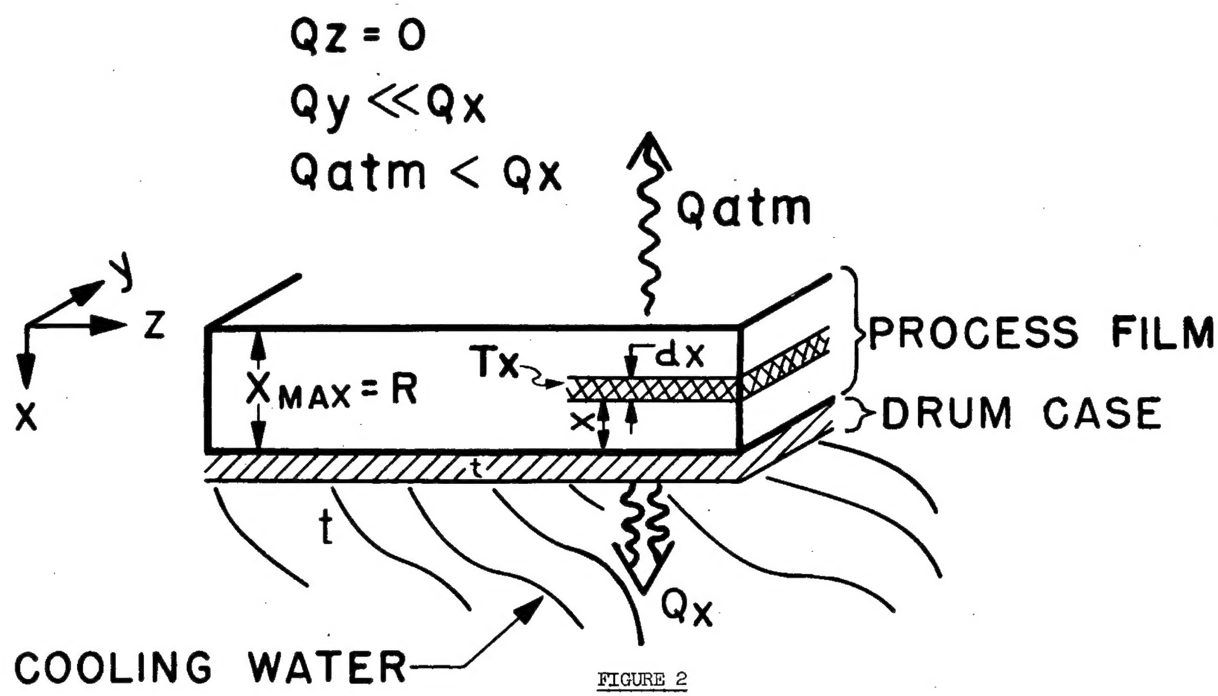


FIGURE 2

FLAKER OPERATION - MATHEMATICAL MODEL

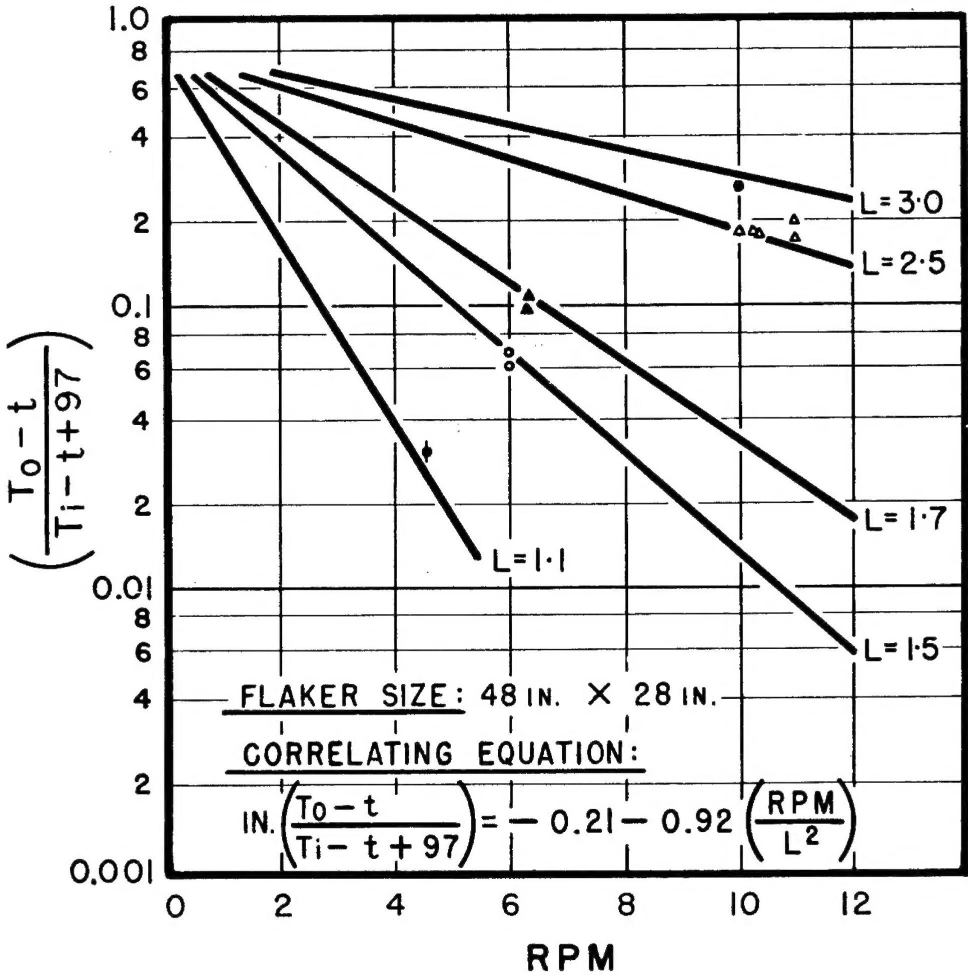


FIGURE 3

FLAKING OF ORGANIC INTERMEDIATE "A"
COMPARISON OF EXPERIMENTAL WITH PREDICTED DATA